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BIOLOGICAL AND ECONOMIC IMPLICATIONS OF SACRAMENTO WATERSHED MANAGEMENT OPTIONS[1]

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ABSTRACT: This paper brings together spatially and temporally explicit mechanistic models of hydrodynamic, water quality, and ecological processes with an economic model to examine water management alternatives for California's Sacramento River and Delta ecosystem, a large-scale watershed. Overallocated water supplies in most years, combined with increasing demand for water for environmental purposes, have created a politically charged atmosphere and a need for quantitative assessment of the implications of policy alternatives. By developing and analyzing a common set of policy scenarios, this integrated framework allows us to consider tradeoffs between agricultural economic factors, water quality, and population dynamics for two at-risk fish species. We analyze two rather extreme types of policy options; one involves structural modifications to change the flow of water within the watershed but no change in water diversions, while the other reallocates water from agricultural users to fish and wildlife. Results suggest that substantial environmental improvements could be made at a relatively modest cost to farmers (1 to 4 percent reductions in revenues) but that those costs could be significant locally. In addition to tradeoffs between farmers and environmental interests, results suggest that policy makers may need to balance competing environmental objectives.
(KEY TERMS: hydrodynamic; water quality; irrigated agriculture; finite-element; particle-tracking.)

INTRODUCTION

The pursuit of traditional agricultural and urban water supplies, hydropower, barge transportation, flood control, and other benefits have altered flow, nutrient, and sediment regimes and destroyed native riparian and estuarine habitats in watersheds throughout the United States, thus threatening many species of plants and animals. In many cases, the introduction of exotic species has further disturbed these ecosystems. In this context, particular fish species are seen as indicators of ecosystem health. Watershed management has undergone revolutionary changes in recent decades as a result of application of the Clean Water Act and the Endangered Species Act. Recent efforts to renegotiate management of these watersheds to protect native species and ecosystems have led to controversial sacrifices of traditional water management objectives (e.g., agricultural and urban water supply, hydropower, and flood control). These controversies are particularly intense in the arid West, where developed water supplies were already insufficient to meet rising demands from traditional users.

California's Sacramento River and Delta system exemplifies this situation. That watershed is the most important single source of water for two-thirds of California's population and more than 7 million acres of farmland, producing 45 percent of the nation's fresh fruit and vegetables (CDWR, 1998). Almost a third of the state's runoff and more than half of all water consumed in the state flows down the Sacramento River. The Sacramento River supplies water for the city of Sacramento and the production of rice, fruit and other crops on farms in the northern Central Valley. The river then flows into the San Francisco Bay and Delta, where pumps in the south Delta export water

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hundreds of miles south to the San Joaquin Valley and to the cities of Southern California and cities in the San Francisco Bay Region (Figure 1). Management of this watershed is thus of immense importance to California and to the agricultural economy of the U.S.

A moderate climate, fertile soils, and an extensive network of water conveyance facilities have enabled California's Central Valley to become one of the most productive agricultural regions in the world. Central Valley farms accounted for more than $10 billion in agricultural sales in 1992. To achieve such high productivity, Central Valley farmers apply nearly 14 million acre-feet of water per year, which they receive from the Federal Central Valley Project (CVP), the State Water Project, local water projects, and ground water sources. The CVP provides 25 percent of total Central Valley water supplies.

While large-scale infrastructure projects "made the desert bloom," those same projects exacted a toll on the natural system. The Sacramento River and Delta once supported large populations of salmon, striped bass, and other fish. That ecosystem is now severely stressed, as indicated by declines in a wide variety of fish and other populations in the Delta (Meng *et al.*, 1994). Several species, including the winter run chinook salmon and Delta smelt, are listed as threatened or endangered under the Federal Endangered Species Act, and several other species are under consideration for listing. Other factors, including toxic chemicals from the watershed (including herbicides and mercury), introduced species (most notably the Asian clam), and a severe drought in 1986 to 1992, have contributed to the ecosystem's decline.

Management of this system and its tributaries is divided among many local, state, and federal agencies, with significant private-sector involvement by farmers and hydroelectric utilities. At the local level, governmental agencies with a role in water management number in the hundreds, including irrigation districts, reclamation districts, and local urban water suppliers. Operation of the main stem is performed substantially by the U.S. Bureau of Reclamation and the California Department of Water Resources, which

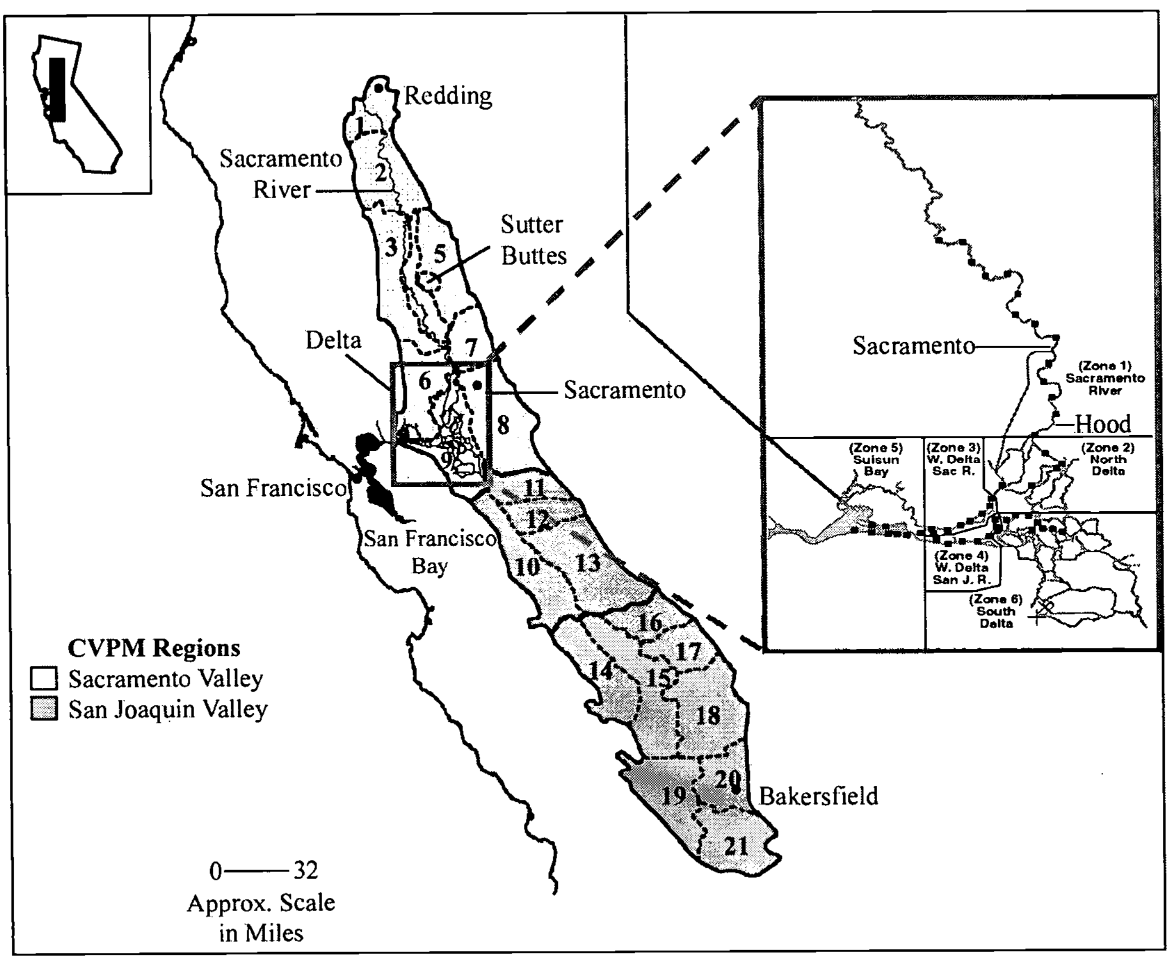

Figure 1. Map of California's Central Valley.

own and operate most of the region's major water storage and conveyance facilities, as well as the massive pumping plants used to divert water southward.

Conflicts over system management have reached crisis proportions and have led to numerous regulatory, legislative, and judicial interventions. In addition, a coordinated state-federal effort, nicknamed CALFED, was formalized in June 1994 with the signing of a framework agreement by four state and six federal agencies with management and regulatory responsibility in the Bay-Delta estuary. An intensive CALFED effort is now underway, working with agricultural, environmental, and urban stakeholders, to develop long-term solutions to problems related to fish and wildlife, water supply reliability, natural disasters, and water quality in the Bay-Delta estuary.

Developing management strategies for sustainable aquatic ecosystems, including finding practical solutions for endangered aquatic species preservation, requires an improved understanding of aquatic ecosystem response to proposed alternatives. To evaluate the costs and benefits of alternative strategies for protecting and restoring sensitive aquatic species, we integrate economic, hydrodynamic, water quality, and ecological models to provide quantitative spatial and temporal assessments of impacts of management alternatives. We proceed by describing each of the four modeling frameworks, including a discussion of linkages among them and presentation of selected base-run results. We then outline the policy framework. Policy options are "drawn from the headlines" – one represents a structural solution proposed by CALFED while the other is based on a controversial 1992 law, the Central Valley Project Improvement Act (CVPIA), that reallocates federal water from agricultural users to fish and wildlife purposes. But these options are stylized for analytical purposes. Next, we present results from the policy analysis and then wrap up with a summary and concluding remarks.

MODELING APPROACH

Water supplies are fully allocated in many years, so providing more water for fish and wildlife will reduce supplies for current water users in those years. By most accounts, that water will come from agriculture. However, the relative costs and benefits of reallocating water from farmers to environmental uses have yet to be quantified. To do so, we construct and integrate a set of models that estimate economic costs (or benefits) to the agricultural sector, spatial and temporal changes in salinity concentrations (an important water quality concern), and population dynamics for two at-risk fish species – chinook salmon and striped bass – from a common set of policy scenarios. We do not attempt to place an economic value on changes in fish populations, preferring instead to frame the tradeoffs in terms of those metrics most of interest to various stakeholders: economic costs and changes in environmental indicators. The overall model structure is depicted in Figure 2. Each of the four major models – economics, hydrodynamics/water quality, striped bass and chinook salmon – is discussed below.

The response of the hydrologic and biological systems and the costs and benefits to the agricultural sector from alternative water management strategies will vary depending on prevailing water supply conditions. The models are run for each of three water year types: dry, wet, and average. Water year scenarios are based on historic water supply conditions. The hydrologic years selected as representative of each water year type are 1992, 1993, and 1984 for dry, wet, and average years, respectively.

Economic Analysis

The focus of the economic analysis is on the agricultural sector. Irrigated agriculture is the dominant land use in the watershed and accounts for roughly 80 percent of basin water diversions, including 12 million acre-feet (maf), 14.4 km^3, that are consumptively used each year. As such, irrigated agriculture is a leading modifying factor for both the quantity and the quality of flows in the Sacramento River and Delta ecosystem.

Baseline Modeling Framework

To assess the effect of alternative water management strategies on agricultural production, we use the Central Valley Production Model (CVPM). The CVPM is a nonlinear, positive mathematical programming model designed to replicate farmer decision-making in response to alternative water price and availability scenarios. The model was developed in conjunction with the CVPIA programmatic environmental impact statement for the purpose of analyzing alternative implementation options (USBR, 1997). While the model's focus is on farmers receiving federal water, it includes all of Central Valley agriculture in recognition of the integrated nature of the hydrologic and economic systems. We use the CVPM to predict how cropping patterns, profit, production technology costs, and commodity pricing change across 21 subregions in response to changes in water allocation. These subregions, which roughly capture spatial and institutional heterogeneity in water districts and

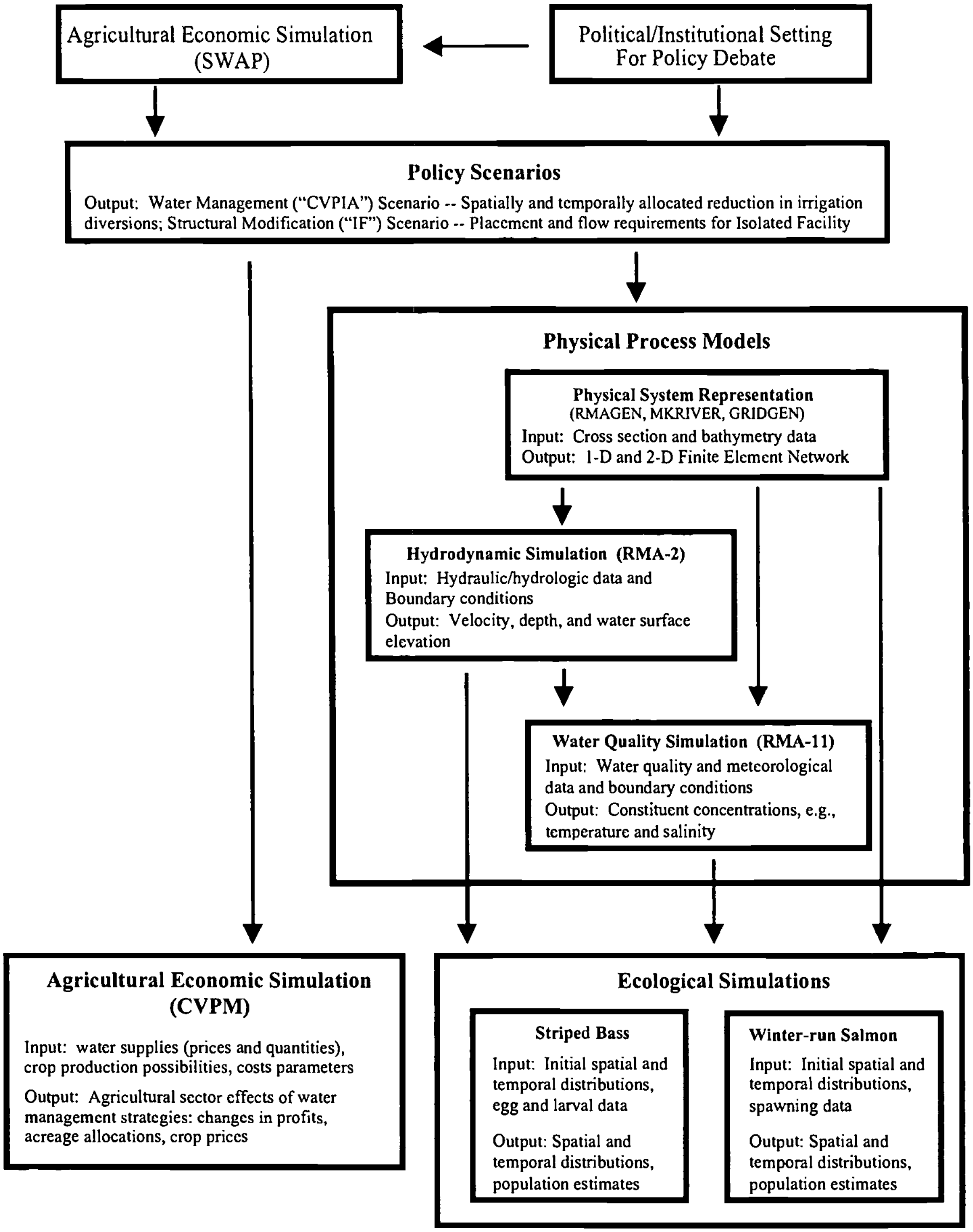

Figure 2. Integrated Modeling Framework.

water delivery sources, form the unit of analysis for this study (see Figure 1). For the purpose of this analysis, we divide the Central Valley spatially into three major units of analysis: the Sacramento Valley, the western San Joaquin Valley (WSJV), and the eastern and southern San Joaquin Valley. These regions play significantly different roles in meeting policy demands for reallocating water from agriculture to the environment. The Sacramento Valley Region includes CVP water users located north of the Sacramento-San Joaquin Delta. The WSJV Region includes "delta exporters," CVP users dependent on water diverted south from the Delta. The eastern San Joaquin Valley Region includes water users receiving water from the state, via the State Water Project and those receiving federal water on a portion of the CVP that is currently operationally distinct from delta operations. Thus, farmers in the eastern and southern San Joaquin Valley will not be directly affected by the policies modeled in this analysis.

The CVPM simulates the decisions of the agricultural producer by assuming that individual farmers make choices based on profit maximization in light of resource constraints, production technology, and market conditions. The model also assumes a competitive market structure so that no single producer can influence the market price of the commodity. However, because California accounts for a significant portion of total U.S. production for numerous crops, large changes in aggregate production *could* affect domestic prices. Accordingly, the model's objective function maximizes producer surplus (net revenue) plus consumer surplus (net value of the products to consumers) subject to available water sources, acreage, and three types of economic response functions: a set of commodity demand functions relating total quantity produced to the market price for each crop; a set of acreage response functions, relating changes in crop acreage to changes in net returns, water availability, and other cost information; and a set of functions describing the tradeoff between applied water and irrigation technology.

Unlike traditional optimization models that depend on observed average conditions, the CVPM employs positive mathematical programming (PMP) to incorporate both marginal and average conditions (Howitt, 1995). To do this, the CVPM adds additional quadratic terms to the linear net revenue function so that the high marginal cost of producing a given crop type beyond its observed level makes it marginally less profitable to grow an additional acre of that crop. In line with economic theory, the added variability in marginal revenue can account for variation between producers in terms of their production costs, variation in yield, variation in crop quality (which affects the crop price), or a combination of all three. The slope of the marginal cost function for each crop is derived using an acreage supply elasticity based on the observed values for crop price, yield, and acreage. The model uses the acreage supply elasticity to calibrate to a set of base conditions, including irrigated acreage by crop and by region and applied water by crop and by region.

The CVPM is also formulated to incorporate the possibility that farmers may alter irrigation technology and management in response to changing water supply conditions. For example, farmers may switch to a higher level of management (e.g., increase labor usage to improve system efficiency) for a given technology, or they may move to a more efficient approach to a given system (e.g., using quarter-mile furrows rather than half-mile furrows). Only with extreme water shortages would a significant switch in capital technology (e.g., switching from an open ditch to a gated pipe delivery system or from a surface system to sprinklers) be predicted. Additionally, the CVPM incorporates the possibility that farmers may substitute ground water for surface water. However, we hold ground water pumping constant for the policy analysis to reflect limited opportunities for sustainable increases in ground water use; each of the subregions studied is in a long-term overdraft situation, and severe overdraft problems are already evident in several key areas. For a more detailed description of the CVPM see USBR, 1999.

The three water year types – dry, average, and wet – are incorporated into the economic model in a slightly different manner than for the physical and biological models. Rather than modeling prevailing conditions for a given year, the CVPM incorporates *averages* of water supply conditions for water year types to more accurately reflect farmers' likely *expectations* of water supplies upon which they base their production decisions. The average base year specified by the CVPM and used in this analysis is defined as the average delivery that would have been available for the hydrologic period 1922 to 1990 had the current storage and delivery infrastructure existed for the entire time span. The dry year is similarly defined as the average delivery that would have been available during the drought period 1928 to 1934. For the purposes of this analysis, we adjust the drought baseline to reflect the 1992 conditions that form the basis for the physical and biological analysis. The wet year is defined as the average delivery that would have been available during the above normal and wet years 1967 to 1971. Calculations from a hydrologic model (PROSIM) developed for CVPIA analysis are used to estimate the average deliveries that would have been available to users if the current water delivery infrastructure had been in place during the specified hydrologic periods (USBR, 1999).

Base Case Results

The base case scenarios reported reflect assumptions about the conditions expected to exist in the year 2020 had the CVPIA not been adopted. Assumptions include existing facilities and land uses as well as projections of future growth, land use changes, and changes in CVP operational policies that are not part of the CVPIA. The level of demand for crop production reflects the crop mix and total acreage projected by the California Department of Water Resources (CDWR) for 2020 (CDWR, 1998). CVP water is priced at the cost-of-service rates published by the USBR (1992) water rate manual. CVPM assumes all contracts will have been renewed by 2020. Additionally, the base case includes adjustable, ability-to-pay water rates based on payment capacity from a 1992 USBR study (USBR, 1997).

Average Water Year Conditions. Gross revenues from crop production for the average year base case total $10.2 billion in average year conditions for the combined Central Valley agricultural regions (Table 1). Revenues net of harvest, production, and irrigation costs in the Sacramento Valley Region total $271 million or $117 per acre. Net revenues in the western San Joaquin Region total $714 million or $371 per acre. Of the 2.3 million irrigated acres of crop production in the Sacramento Region, rice, orchard, grain, and field crops make up more than 65 percent of the crop mix. This contrasts sharply with the crop mix in WSJV in which cotton and truck crops alone make up 55 percent of the 1.9 million acres in that region (Table 2).

The amount of applied irrigation water in these regions may help to explain the disparate crop mix. Water applications for rice in the Sacramento Region, for example, average 6.3 acre-feet (af) per acre per year. In contrast, approximately 3.2 af per acre per year of water is applied to cotton, the most widely grown crop in the western San Joaquin Region. While water applications reflect differences in crop water demand, only a portion of applied water will be used by plants. For example, evapotranspiration for rice is less than 4 af per acre, while that for cotton is approximately 2.5 af per acre. Water applications greater than crop evapotranspiration help leach salts through the soil profile and ensure that minimum water requirements are met at all points in nonuniform fields. Some of that water will infiltrate to ground water aquifers or will be lost to salt sinks, while another portion may become surface runoff, available for immediate reuse. Water balances reflect average return flows. In total, 8.2 maf per year is applied to agricultural fields in the Sacramento Region and 5.7 maf is applied in WSJV. In terms of the agricultural value of one acre-foot in these regions, we estimate that net revenue averages $126 per af for applied water per year in WSJV, compared to only $33 per acre-foot of applied water per year in the Sacramento Valley. This difference may be attributed to the higher yields and higher value crops produced in the San Joaquin Valley. Cotton, which represents one-third of the acres planted in the San Joaquin Valley, returns gross revenues of $1,000 per acre. For comparison, the most widely planted crop in the Sacramento Valley, rice, returns average gross revenues of $600 per acre (USBR, 1999).

Dry Year Conditions. Average surface water supplies decline by 20 percent for the dry year base case relative to the average year. The dry year results reflect a higher marginal value of applied water. Relative to the average year condition, net revenue in the Sacramento Valley falls by 4 percent to $261 million. In the San Joaquin Valley, net revenue falls by 11 percent to $635 million (Table 1). The restricted water supply raises the marginal cost of additional acreage

TABLE 1. Effect of CVPIA Policy Scenarios on Gross and Net Revenues to Agricultural Producers (in $ million).

	Sacramento Valley		Western San Joaquin Valley		Total Agriculture*	
	Gross Revenue	Net Revenue	Gross Revenue	Net Revenue	Gross Revenue	Net Revenue
Average Year Baseline	**2,157.43**	**271.14**	**4,043.18**	**714.36**	**10,158.12**	**2,269.81**
1.2 maf Water Allocated for Environmental Purposes From:			**Changes From Average Year Baseline**			
Sacramento Valley	-82.61	-67.36	1.50	0.87	-79.01	-65.00
Western San Joaquin Valley	5.08	3.40	-175.36	-95.66	-162.17	-86.63
Dry Year Baseline	**2,144.74**	**260.76**	**3,882.87**	**635.11**	**9,858.19**	**2,093.18**
800,000 af Water Allocated for Environmental Purposes From:			**Changes From Dry Year Baseline**			
Sacramento Valley	-61.83	-49.27	0.88	0.80	-59.80	-47.44
Western San Joaquin Valley	5.40	4.12	-202.21	-75.68	-190.49	-65.90

*Total includes values from Eastern San Joaquin Valley, as well as those from the Sacramento and Western San Joaquin Valley regions.

TABLE 2. Effect of CVPIA Policy Scenarios on Irrigated Acreage in Average Year Conditions (in 1,000 acres)

	Sacramento Valley			Western San Joaquin Valley			Total Agriculture		
		Environ. Water From:			Environ. Water From			Environ. Water From	
	Base	Sacramento Valley	West San Joaquin Valley	Base	Sacramento Valley	West San Joaquin Valley	Base	Sacramento Valley	West San Joaquin Valley
Irrigated Pasture	187	-29	1	19	0	-8	206	-29	-7
Alfalfa hay	138	-10	2	170	0	-37	308	-10	-35
Sugarbeets	97	-2	0	31	0	-2	128	-2	-2
Field Crops (Corn, Dry Bean, Oilseed, Alfalfa Seed)	324	-15	0	173	0	-21	497	-15	-21
Rice	476	-70	0	3	0	-1	479	-70	-1
Truck (Onion, Melon, Potato, Misc. Vegetables)	132	0	0	370	0	-2	502	0	-2
Tomato (Fresh Tomato, Processing Tomato)	169	-2	0	122	0	-6	291	-2	-6
Orchard (Almonds, Peaches, Prunes, Walnuts)	388	-1	0	125	0	-1	513	-1	-1
Grain (Wheat, Misc. Grain, Misc. Hay)	325	-10	0	99	0	-7	424	-10	-7
Grapes	73	0	0	101	0	-1	174	0	-1
Cotton	0	0	0	698	0	-105	698	0	-105
Subtropical (Citrus, Olives)	14	0	0	16	0	0	30	0	0
TOTAL	**2,324**	**-141**	**3**	**1,927**	**1**	**-190**	**4,251**	**-140**	**-187**

such that the valley wide total of irrigated acreage is 4 million acres, or 200,000 acres less than the average year condition. Although total acreage falls in comparison to the average water year, the cropping pattern retains the same proportional cropping mix within a margin of 0.1 percent.

Wet Year Conditions. Under wet year conditions, water users apply an average valley wide 11 percent increase in surface water supplies over average year conditions. Gross revenues from agricultural production in the wet year closely match the average year results of $10.2 billion. Furthermore, since costs do not change significantly in wet year conditions, net revenues were not significantly different from average conditions. Given that wet year conditions do not significantly alter crop prices or production costs, we assumed that agricultural production responses to policy scenarios will be no greater than those of the average year condition.

Hydrodynamic and Water Quality Models

The central link in the set of interrelated physical and biological models used in this project is a hydrodynamic model describing those properties of the riverine and estuarine system necessary for characterization of system water quality and ecology. The foundation for the hydrodynamic modeling framework is a multi-dimensional finite element representation of the surface water system developed by Resource Management Associates (RMA) and adapted for this research project for analysis of policy options for the Sacramento River and Delta system. Among the advantages of this approach is its flexibility to be adapted to a wide variety of surface water bodies, rivers, estuaries, lakes, reservoirs, and coastal systems of complex geometry. Both the hydrodynamic and water quality models (discussed below) use the same network of elements in either one or two dimensions, depending on the need for detailed description of variables. For this study, the Sacramento River and

Delta channels were represented by one-dimensional elements, and San Francisco Bay was represented by two-dimensional, depth-averaged elements.

Hydrodynamic Model

As a first step, the geometry of the system is described by a representative finite element network produced from geometric or geographic information sources with a graphical preprocessor. Given the system geometry, the hydrodynamics of the system are then simulated with RMA-2 (King, 1996). This hydrodynamic model provides one-dimensional and depth-averaged two-dimensional representations of variations in water velocities and depths over the modeled domain for a given simulation period (the Sacramento River and Delta are modeled in one dimension, while the Bay is modeled in two dimensions). Spatial and temporal distributions of velocity, depth, and water surface elevation are calculated, based on conservation of water mass and momentum, by solving momentum and continuity equations.

Boundary conditions for RMA-2, including upstream reservoir releases, tributary inflows, agricultural and municipal withdrawals, and tidal influences at Golden Gate, are specified at half-hour, hourly, or daily intervals, depending on the available data. In addition, CDWR provided monthly estimates of Delta consumptive use, defined as agricultural withdrawals minus return flows (CDWR, 1995). Model output provides water velocity, depth, and water-surface elevations every half-hour for each finite element node (approximately 8,050 locations) over the simulation period.

To the extent possible, the model was calibrated to historical data from CDWR, the U.S. Geological Survey (USGS), and the National Oceanic and Atmospheric Administration (NOAA). A 15-month period, April 1992 through June 1993 was chosen for the calibration. This period corresponds to the critical April through June period for striped bass for both years and to the 15-month freshwater rearing period of winter-run chinook salmon. We compared hydrodynamic simulation results to field data to ensure that the model provides a reasonable representation of the system. Along the main stem of the Sacramento River where flows are unidirectional, simulated and observed flows were compared. At selected locations, accretions and depletions were adjusted to account for ungaged inflows, local diversions, and ground water interactions. In San Francisco Bay and the Delta where tidal action causes flow reversal, the simulated and measured water surface elevations were compared. The calibration process involves adjusting selected physically based model parameters to improve model behavior when compared to field observations (see Anderson, 2000, for more details). The first nine months of this time period coincide with the end of a six-year drought. The low water levels and high water temperatures associated with the prolonged drought provided the most unfavorable conditions for juvenile salmon survival in the recent period of record. Likewise, warm water temperatures in 1992 probably increased striped bass egg and larval mortality. Thus, analysis of management alternatives under these unfavorable environmental conditions provides insight into their effectiveness for preserving fish species.

Water Quality Model

Given the hydrodynamic representation of a system provided by RMA-2, the finite element model RMA-11 provides dynamic descriptions of water quality (King, 1995). Spatial and temporal distributions of water quality constituents are calculated using the advection-dispersion equation. We focus on water temperature and salinity constituents (e.g., TDS), parameters important to striped bass and salmon growth and mortality. Higher temperatures increase striped bass development and growth rates. However, because higher temperatures also increase egg and larval mortality rates, higher temperatures are detrimental to striped bass during early life. Excessively high water temperatures are also known to harm juvenile salmon (in the chinook's earliest life stages, eggs and yolk-sac larvae are susceptible to impairment or mortality at temperatures above 13.3°C). Juvenile chinook salmon migrate through the Delta and are unable to tolerate high salinity levels before they undergo the physiological changes necessary to move from freshwater into saline estuarine and ocean water. In addition, high salinity concentrations in drinking and irrigation water can harm human and crop health.

Water quality simulation results were compared to field data from CDWR and USGS to ensure that the model provides a reasonable representation of the system. Water temperatures are strongly influenced by the mechanisms of heat exchange at the air-water interface; hence, meteorologic data, including air temperature, wind velocity, relative humidity, cloudiness, etc., provide important inputs to the water quality model. Calibration efforts focus on adjusting evaporation coefficients until simulated results provided acceptable agreement with field data. Similarly, salinity changes within the system, ranging from freshwater river flows to ocean water at Golden Gate, are represented in the model. Calibration efforts for salinity focused on modifying hydrodynamic eddy dispersion coefficients and providing a representation of salinity of agricultural return flows until the simulated salinity gradients matched field data.

Fish Population Models

The final component of the modeling framework includes two particle/organism transport models extended for partially explicit individual-based mechanistic modeling of fish populations, thus integrating hydrodynamics, water quality, and ecological processes. Our approach involves formulating models of individual fish (Botsford, 1992) based on available information on life history and response to environmental conditions (e.g., the dependence of growth and mortality rates on temperature and salinity) and running them in the context of the hydrodynamic and water quality models for specific time periods. The species modeled are the striped bass (*Morone saxatilis*) and the winter-run chinook salmon (*Oncorhynchus tschawytscha*).

Striped Bass

We chose striped bass as an example because more data are available on its distribution and abundance than on any other fish in the Delta, it supports a significant sport fishery, and the decline in striped bass in the 1970s was an early indicator of declining ecosystem health. Striped bass were introduced to this estuary in the 1870s. Initially the basis for a large commercial fishery, for the past several decades they have been fished only recreationally. The adult population declined from 3 million fish during the 1960s to less than 1 million today. Recruitment to this fishery, in terms of a young-of-the-year (YOY) index was shown to depend on a combination of Sacramento River outflows and diversions (Chadwick *et al.,* 1977). Since 1976 (a drought year), however, the YOY index has been below those predictions (Stevens *et al.,* 1985). Early survival is related to the distance from the mouth of the Bay to the point at which salinity has dropped to 2 ppt. (Jassby *et al.,* 1995). This point (referred to as X2 in related literature and in policy discussions) is an indicator of flow conditions in the Delta. As shown by Jassby *et al.* (1995), a combination of flows and diversions during the larval period and the following summer provide a moderate fit to survey data. These results indicate that water management and concentrations of various toxicants significantly influence striped bass population dynamics. We developed a model of the mechanisms underlying these relationships and used that model to predict future population behavior in response to water management scenarios.

We linked the model of egg and larval striped bass to the hydrodynamic model using simulated particles. The particles, each representing groups of identical individuals, were "released" into the physical model and moved passively as controlled by the advection and dispersion in the physical model. For each of the model years 1984, 1992, and 1993, eggs were released into the physical model base run at the time and location at which they were sampled in the California Department of Fish and Game's egg and larval survey. In addition, larvae in the size range of 4 to 14.5 mm were released into the model at the first model time step. A total of approximately 30,000 particles per run were released. After release, the eggs and larvae, as represented by the individuals in each particle, developed and grew until reaching a size of 14.5 mm – the maximum size for which the model is valid – or died. Development, growth, and mortality were represented by temperature-dependent functions developed from laboratory data. At each model time step, the temperature for each particle is taken from the water quality model.

Before using the model to examine hypothetical management changes, the model base runs for each year were compared to data from that year, and the model parameters were adjusted to give the best fit across years. Because of the dynamic nature of the system (i.e., advection in the rivers and tidal movement dispersing individuals in the estuary), it was necessary to aggregate the data and model output into regions. Six spatial zones were used representing the Sacramento River (Zone 1), the North Delta (Zone 2), the West Delta-Sacramento River (Zone 3), the West Delta-San Joaquin River (Zone 4), Suisun Bay (Zone 5), and the South Delta (Zone 6). These six zones are shown in the inset in Figure 1.

Winter-run Salmon

Winter-run chinook salmon were placed on the Federal Endangered Species list in 1991 and ever since have been a critical element in the management of the Sacramento watershed. Similar to the striped bass model, a particle-tracking algorithm was modified for this research to represent various life stages of juvenile chinook salmon. The newly developed particle-tracking model, SAMTRK, assesses effects of changes in hydrodynamic and water quality conditions on juvenile chinook salmon survival, growth, and migration (Anderson, 2000). In SAMTRK, discrete particles represent individuals or subpopulations of juvenile chinook salmon at various life stages as they move through the simulated environment from spawning redds upstream through the Delta and finally into the ocean. Life stages modeled are eggs, yolk-sac larvae, fry, and smolts. In the model, simulated environmental factors such as flow rate, water temperature, and salinity (from the hydrodynamic and water quality models) affect simulated survival, growth, and migration of the juvenile salmon.

For this study, the model was calibrated to historical data for April 1992 through June 1993 from the U.S. Fish and Wildlife Service. To simulate impacts of proposed management alternatives, appropriate modifications were made to the hydrodynamic and water quality models. SAMTRK was then rerun with the modified hydrodynamic and water quality results. Impacts of the management alternatives on juvenile chinook salmon populations were then assessed relative to the historical conditions (see Anderson, 2000, for model description and results).

DEVELOPMENT OF POLICY SCENARIOS

The search for policy options for calming the highly charged conflict among stakeholders in the Sacramento Bay and Delta "water wars" has produced numerous suggestions. We focus on two options in this analysis. Each represents an extreme in terms of the types of policies being contemplated or implemented. The first, the "CVPIA scenario," involves a reallocation of water from federal water users to environmental purposes. The second alternative, the "CALFED IF scenario," involves structural changes in the delta, an "isolated facility," that moves the location of diversions for the large pumps sending water south to the San Joaquin Valley and Southern California. Our representation of both policy options is highly stylized, reflecting conservative assumptions, and designed to depict the types of changes that might occur in either case. Our results should not be taken as indicative of changes that necessarily will occur with either option. Table 3 indicates the combinations of policy scenario, model, and water year results discussed below; in the interest of space, only a subset of the possible combinations is presented.

Water Allocation (CVPIA) Scenario

The CVPIA calls for approximately 1.2 million acre-feet of water (800,000 acre-feet in a dry year) to be allocated for environmental purposes. To be conservative, we assumed that the full amount of the environmental water would come exclusively from farmers' water supplies. Of this total, 800,000 acre-feet of water are to be used during "average" hydrologic conditions to enhance instream flows and/or aid in water temperature or pumping controls in the Sacramento River system. During dry hydrologic conditions, this allocation is reduced to 600,000 acre-feet. In addition, 250,000 acre-feet will be allocated to wildlife refuges and 150,000 acre-feet will come from reductions in Trinity River diversions.

Although the law is clear on the quantity of water to be made available, it is less clear on how the diversion reductions will be allocated. Economic efficiency dictates that water be allocated from the least efficient water users first. The economic value of agricultural water use varies significantly between the Sacramento and San Joaquin Valleys. However, institutional and operational constraints may limit the transfer of water between the two basins, as is necessary to equilibrate the economic values and attain an efficient solution. In all likelihood, the CVPIA allocation requirement will be met by altering a combination of Sacramento and San Joaquin Valley diversions, but the precise allocation will depend on a wide variety of factors. To account for this uncertainty, we modeled water coming from either the Sacramento or western San Joaquin regions, but not both, for the average and dry water years. We assumed that water supplies will be sufficient in wet years to meet environmental requirements without reducing farmers' water supplies. Our scenarios are thus:

TABLE 3. Policy Scenarios Analyzed by Model Type and Water Year.

Policy Scenario	Economic Analysis	Water Quality Analysis	Biological Analysis	
			Striped Bass	Chinook Salmon
CVPIA – Sac	YES* (dry, average)	NO**	YES* (dry, average)	NO
CVPIA – SJV	YES* (dry, average)	NO**	YES* (dry, average)	NO
Isolated Facility	NO	YES (dry, average, wet)	YES (dry, average, wet)	YES (dry, wet)

*Wet year not analyzed because water supply changes due to the CVPIA in a wet year would be zero.
**Scenarios analyzed, but results not presented in this paper due to space constraints.

- Average Water Supply Conditions (1.2 maf diversion reduction): (a) assume that all reductions come from the Sacramento Valley and in-Delta farmers, and (b) assume that all reductions come from south Delta exporters (essentially the WSJV).

- Dry Water Supply Conditions (800,000 af diversion reduction): (a) assume that all reductions come from the Sacramento Valley and in-Delta farmers, and (b) assume that all reductions come from south Delta exporters (essentially the WSJV).

The economic model is an annual model (e.g., it has a one-year time step), while the remaining models run on a 30-minute time step. As a method for linking all models for the policy scenarios, we estimate monthly changes in water flows. For each scenario, we allocated the reductions in diversions temporally, over the ten- month irrigation season, and spatially, among the CVPM regions, by applying the Statewide Water and Agricultural Production Model (SWAP) to calculate the economically efficient allocation of water reductions within each region. If, in actuality, diversion reductions are not allocated efficiently within a region due, for example, to institutional constraints, our cost estimates will underestimate farmers' costs of the diversion reductions. A "cousin" of CVPM, SWAP is a nonlinear PMP economic model that assesses the effect of water management scenarios on the value of California agriculture. SWAP is related to CVPM in that it uses CVPM regions and base data (including acreage, prices, and water allocations), but it extends CVPM by allocating water to agricultural users on a monthly, as opposed to yearly, basis. (For a more detailed description of the SWAP model, see Howitt *et al.,* 1999).

Before analyzing the policy scenarios, we adjust water delivery baselines in SWAP based on monthly diversion data from the hydrodynamic model to improve compatibility across models. For example, diversion data from 1992 was used to approximate the dry year baseline. The imputed data matched the model calibration data within 20 percent. Wet year policy scenarios were not run because agricultural production activities are essentially unchanged in wet years relative to average year conditions. Two average year and two dry year policy scenarios were run using the SWAP model to determine monthly water reductions by regions. These policies consisted of reducing water allocations by 1.2 maf in the average year and 800,000 acre-feet in the dry year to the Sacramento and San Joaquin Valley regions, individually. The monthly reductions were used in the hydrodynamic model. For the purpose of economic analysis, the reductions were aggregated to yearly reductions and subtracted from the base case water allocations in the CVPM model.

After the economic analysis determined the optimal allocation pattern for diversion reductions for each scenario, hydrodynamic, water quality, and ecological simulations were conducted to determine impacts of these alternatives on striped bass eggs and larvae. The monthly allocation changes were aggregated to annual changes for use in the CVPM and subtracted from the base case water allocations in the CVPM model and were disaggregated, assuming a uniform allocation within a given month, for use in the hydrodynamic model. Since the flow reductions were computed by region and not by specific diversion point, in the hydrodynamic model RMA-2, the Sacramento Valley reductions in diversions were modeled as inflows at locations along the Sacramento River corresponding to each region. The San Joaquin Valley diversion reductions were modeled as increases in the San Joaquin River flow.

Structural Modification (CALFED Isolated Facility) Scenario

One CALFED proposal involves construction of a diversion canal, known as the "isolated facility" (IF) (CALFED, 1998). The IF would divert water from the Sacramento River north of the Delta at Hood and convey it around the perimeter of the Delta, delivering the diverted flow to Clifton Court Forebay. Proposed capacities of the isolated diversion canal range from 5,000 cfs (140 cms) to 15,000 cfs (425 cms). Operations of the IF would require a combined minimum pumping rate for the state and federal facilities in the southern Delta of 1,000 cfs (28.3 cms) from July through March. Delta pumping would not be allowed from April through June to protect vulnerable juvenile fish present in the Delta during that period.

To develop an IF scenario, we examined the impact of diverting the same amount of water at Hood that was diverted at the state and federal pumping facilities during the period of July 1992 to June 1993. Historical withdrawals from south Delta pumps were compared with simulated base case flows at Hood to ensure that the hypothetical withdrawal at Hood would not exceed river flow and that the combined withdrawals did not exceed the proposed maximum capacity of the IF. The minimum pumping requirements for July through September were divided equally between the two south Delta pumping plants – Clifton Court Forebay (CCF) and Tracy. The differences between the minimum Delta pumping rates and historical withdrawals for July 1992 through March 1993 were withdrawn at Hood. For this management scenario, no pumping was allowed at Clifton Court or

Tracy in the period from April through June. The entire historical withdrawal for April through June 1993 was diverted at Hood. A screening efficiency of 70 percent was assumed for the IF withdrawal (Anderson, 2000).

RESULTS OF POLICY ANALYSES

Economic Analysis

To examine the cost of various policy scenarios, we report changes from the appropriate base case (normal year or dry year) in farmers' profits, cropping patterns, and water use associated with each of the water management (CVPIA) scenarios. Because the Isolated Facility (CALFED) scenario holds total diversions constant, we assumed farmer production practices would be unchanged for that scenario.

Allocate Environmental Water Supply from Sacramento Valley Region (Average Year Results)

Reallocating 1.2 million acre feet of water from Sacramento Valley farmers to environmental uses results in a reduction in gross revenue of $83 million, which represents a 0.8 percent decrease from Central Valley agriculture and a less than 4 percent decrease from the Sacramento Region baseline (Table 1). Taking production, harvest, and irrigation costs into consideration, we see a decrease in net revenues of $67 million from the Sacramento Valley Region, which represents a 3 percent reduction in net revenue for both agricultural regions combined and a 25 percent reduction from the Sacramento Region alone. Taking water from the Sacramento Region results in a slight increase in revenues to the western San Joaquin region (less than 0.5 percent) due to a small increase in the endogenously determined market price of the crop. Price increases, which average only 0.26 percent over all crops, result from a reduction in the total production of those crops.

The policy scenario results in the retirement of 141,000 acres or 6 percent of the agricultural acreage in the Sacramento Valley region (Table 2). Although total acreage shifts are modest, closer inspection of the changes indicates potentially significant local effects. Approximately half of the acreage reduction comes in the form of reductions to rice farming. Two-thirds of the reductions in rice acres occur in just two regions (Regions 3 and 5, Figure 1). Another one-fifth of the retired land is from irrigated pasture. Reductions in irrigated pasture are similarly concentrated, with 70 percent of the losses occurring in Regions 3b, 5 and 7. These results are consistent with the fact that these crops are the most water intensive of those grown in the region and that crops tend to be spatially concentrated due to variations in local soil and water supply conditions.

Allocate Environmental Water Supply From the Western San Joaquin Valley Region (Average Year Results)

The higher value of agriculture in WSJV leads to slightly more significant impacts to revenue as a result of decreasing the water allocation to this region (Table 1). Net revenues decline by $96 million or 4 percent of the total for both regions (13 percent of the total for WSJV only). Gross revenues are reduced by $175 million, a 4 percent reduction in WSJV.

Of the 190,000 acres that are retired as a result of the reallocation of environmental water from WSJV, 105,000 acres come out of cotton production (Table 2). In addition, acreage planted in alfalfa hay and field crops is reduced by 31 percent. Once again, these effects may be concentrated spatially, with Regions 10 and 14 experiencing 20 percent reductions in their base case cotton acreages and nearly 30 percent reductions in their alfalfa hay. As expected, reductions in applied water mimic reductions in irrigated acreage. Total water applied to irrigated pasture is reduced by 53 percent, the highest percentage reduction of any crop in either region. This may be due to low marginal revenue for pasture relative to other crops in the WSJV Region.

Allocate Environmental Water Supply from Sacramento Valley Region (Dry Year Results)

Reallocating water for environmental purposes in the dry condition has similar impacts to gross and net revenues. Gross revenues are reduced by $62 million, a 3 percent reduction from the dry year baseline figure for the Sacramento Valley region (Table 1). Net revenues are reduced by 19 percent of the baseline level in the Sacramento Valley to approximately $212 million, i.e., to $92 per acre from $114 per acre irrigated in the dry year baseline. Irrigated acreage in the Sacramento Valley region is reduced by 102,000 acres or 4.5 percent of the total agricultural acreage in the Sacramento Valley. Changes in cropping patterns are similar to those for the average year conditions.

Allocate Environmental Water Supply From the Western San Joaquin Valley Region (Dry year Results)

Reallocating 800,000 af of water from WSJV reduces gross revenue by 5 percent to $3.7 billion in that region (Table 1). Net revenues fall $76 million to $559 million (from $361 per acre to $322 per acre irrigated in the dry year baseline). Irrigated acreage is reduced by 220,000 acres, a 3 percent greater reduction than under average year conditions.

Isolated Facility

Our IF scenario holds water use constant. Consequently, we do not estimate any changes in production activities or in farmers' net revenues from crop production. In fact, farmers are likely to experience both benefits and costs from an IF. The value of the benefits and costs, and indeed whether net benefits are positive or negative, is unknown at this time. One potential benefit of an IF is an increase in water supply reliability; by moving the diversion point out of the Delta and into the Sacramento River, the IF could reduce (or eliminate) the need to curtail pumping to protect water quality and fish in the southern Delta. However, both the potential increase in reliability and the economic value of that increase are unknown. Farmers would also benefit from improvements in irrigation water quality in dry years (discussed below), but quantifying that benefit is beyond the scope of this study. In terms of costs, annualized construction, operation, and maintenance costs for the IF are estimated to be $104 million (CALFED, 1999). That cost may be borne by some combination of agricultural and urban water users and taxpayers. Urban water users would likely bear a majority of the costs, but we are unable to determine the portion that might be allocated to farmers or whether those costs would be experienced as a lump-sum payment or would affect water prices, and thus could influence production decisions.

Water Quality Analysis

The impacts of policy scenarios on water quality are most pronounced in the IF simulations and thus are reported here. We focus on a comparison of salinity (TDS) concentrations throughout the Delta, with particular attention to the quality of Delta water exports. Salinity is a constituent of concern to both agricultural and urban water users, reflects tidal intrusion of salinity from the Bay, is monitored at agricultural and urban water withdrawal locations within the Delta, and has been the target of EPA water quality regulations. Simulations are partially dependent on hydrologic year type (i.e., wet, dry, or normal). Results suggest that operating an IF would be marginally beneficial under normal or especially wet conditions, but IF operation during dry periods is critical in providing water supplies from the Delta that meet water quality criteria.

Water quality in summer months is traditionally worse than in other times of the year because it is a time of low natural flows and peak irrigation demand, so the analysis focuses on the spring/summer time frame. During the normal and wet conditions experienced during 1984 and 1993, the range of concentrations predicted for withdrawals from CCF rarely exceeds 300 mg/l, while concentrations at the IF remain constant at 100 mg/l (Table 4). Since concentrations in both scenarios meet the general salinity criterion of 500 mg/l, there is no significant water quality benefit to an IF.

TABLE 4. Comparison of Salinity Concentrations (mg/l) of Delta Exports From the Isolated Facility (IF) and From Clifton Court Forebay (CCF) Under Various Water Year Types.

	Water Year		
Withdrawal Location	**1984 (average)**	**1992 (dry)**	**1993 (wet)**
Isolated Facility	100	100	100
Clifton Court Forebay	160-320	230-890	140-290

However, results for a dry period (1992) show stark contrasts. Drought conditions exacerbate problems associated with the temporal confluence of low natural flows and high demand for irrigation and urban water uses. During this period, CCF water quality degrades considerably due to low flows of fresh water into the Delta. In the "without policy" (base case) scenario, salinity concentrations of withdrawals from CCF increase upwards of 800 mg/l near the end of the baseline simulation period in 1992. Exports under this scenario are severely compromised. In contrast, concentrations of withdrawals from the IF show very good water quality in the same time period. IF concentrations again reflect a freshwater concentration of 100 mg/l (Table 4). In other words, operation of the IF even during dry years does not cause tidal salinity to encroach into the river and affect export concentrations. The water quality benefits of operating an IF are significant only when Delta water supplies are scarce.

A visual confirmation of these results can be seen when water quality simulations are compared spatially throughout the Delta at particular snapshots in time (Figures 3 and 4). Concentrations of exports from CCF during normal or wet years such as 1984 remain of good quality. Salinity concentrations at CCF show roughly 200 mg/l at the end of June 1984 (Figure 3, "Base Case"). This occurs because sufficient flows in the Sacramento River push tidal salinity seaward (west in Figure 3) so that pumping from the South Delta draws water of relatively low salinity (200 mg/l). Slightly higher salinity levels in the Southeastern Delta are due in part to agricultural runoff in the San Joaquin River, which enters the Delta from the southeast and is "trapped" there by the high Sacramento River flows and high pumping at CCF.

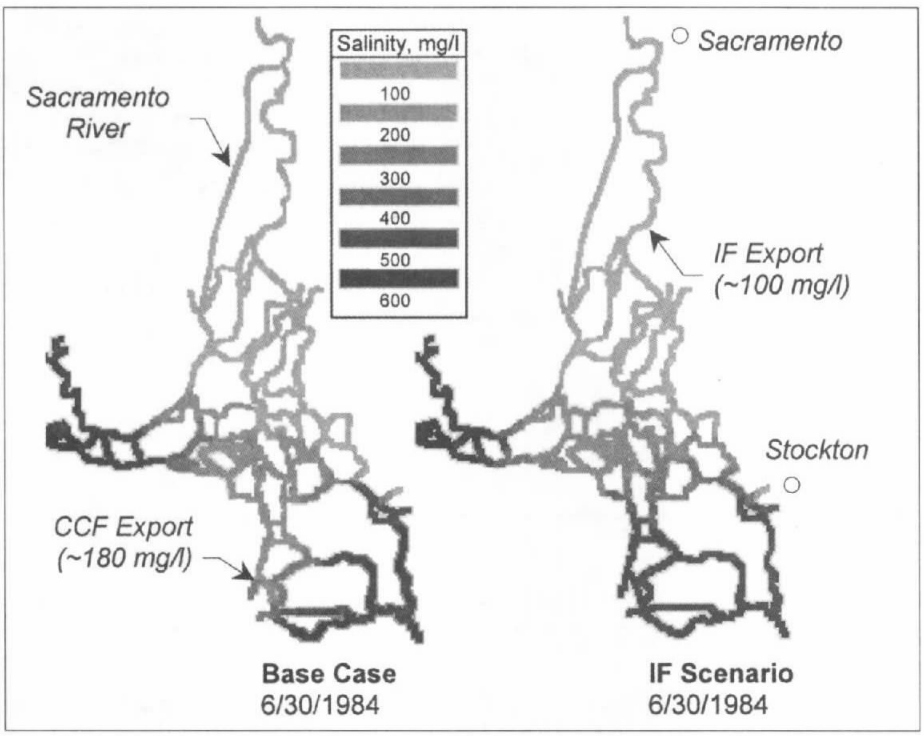

Figure 3. Spatial Comparison of Salinity Concentrations, With and Without an Isolated Facility, June 1984.

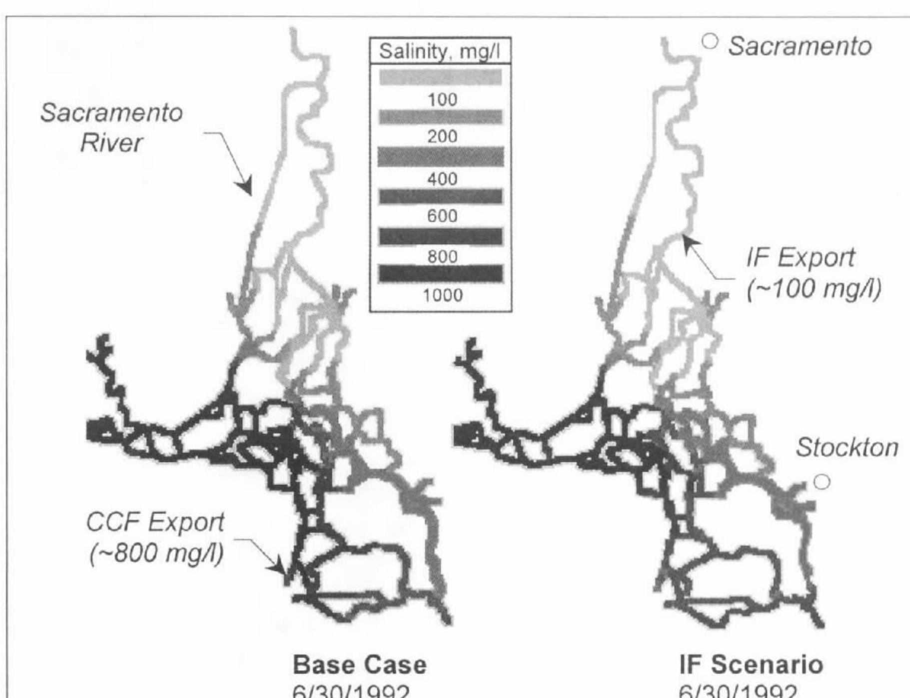

Figure 4. Spatial Comparison of Salinity Concentrations, With and Without an Isolated Facility, June 1992.

In 1992, high salinity water encroached further into the Delta, drawn toward CCF because Sacramento River flows were low, and concentrations in exports from the IF were less than those from CCF at all times. Results at the end of May show concentrations of over 600 mg/l being drawn toward CCF in Old River in the base case, while those in the IF scenario are approximately 350 mg/l. It is more meaningful, however, to compare base case results at CCF with those of the IF scenario at Hood (denoted IF Export in Figures 3 and 4). This comparison allows water quality of State Water Project (SWP) withdrawals under the two scenarios to be contrasted. Under the base case, SWP withdrawals would be approximately 400 to 600 mg/l at CCF. Under the IF scenario, SWP water quality would be 100 mg/l. Near the end of the simulation period in 1992, salinity concentrations in withdrawals from CCF increase enough to exceed general standards. In this case, concentrations at CCF approach 800 mg/l (Figure 4, "Base Case"; note the increase in the salinity legend scale between Figures 3 and 4). Spatial comparisons of water quality results reveal the actual cause of degradation of Delta export water quality – advection of salinity from the Bay south toward pumping facilities – in dry years when the IF is not operated (Loeb, 2001).

Biological Analysis

The fish population models estimate the distribution of fish of given size or life stages at all points along the spatial and temporal continuum modeled. As one measure of the implications for fish populations of the various policy scenarios, we consider changes in that distribution. Figure 5 depicts those changes for striped bass for the dry year CVPIA scenario in which all water is taken from agricultural water users in the western San Joaquin Valley and water flows are increased in the San Joaquin River. The six frames in Figure 5 correspond to the six spatial zones illustrated in Figure 1. The graphs for each region represent the fractional change (i.e., percent change divided by 100) in the number of striped bass eggs or larvae of each size class located in a given portion of their habitat on a given date, relative to the base case. We assumed that the base case model run represents historical conditions. As such, dividing the management output by the base case shows the change in the number of surviving eggs and larvae induced by the change in management. The model outputs are plotted with a log scale for the fractional change. As such, a fractional change on the log scale of -0.5 (black) means that the management run has 0.32 (i.e., 32 percent) of the number of individuals in the base run. Likewise, a fractional change of 0.5 (white) on the log scale indicates that the management run has 3.2 times the number of individuals seen in the base run.

It appears as though the influence of these changes in water allocations under such extreme dry year conditions would be to reduce the number of fish in Zones 3, 4, and 6, the southern and western portions of the Delta. Extra water input into the San Joaquin River may push individuals out of those regions. These zones may also benefit from reduced "reverse flows," water moving from Zones 3 and 4 into 6, due to reduced pumping of irrigation water from the south Delta. Finally, because it is a low flow year, the increased flows from the reallocation are not sufficient to push the individuals out of the model domain past Carquinez Straits, so they are retained in Suisun Bay. This redistribution of striped bass is likely to be beneficial to the population because food availability is higher in this area than in the Delta (Jassby *et al.*, 1995). Reducing the number of fish in the south Delta is among the most important requirements for improved fish survival rates because mortality of fish entrained in the diversion pumps is essentially 100 percent.

Effects are less pronounced for the CVPIA-Sacramento reduction scenario in both years and for the SVPIA-San Joaquin reduction scenario in 1984. Similar but less extreme results are found for the San Joaquin scenario under average year conditions as were seen in the 1992 output. In particular, the increase in Zone 5 is modest. In this case, the additional water pushes more than 100 times as many individuals past Carquinez Straits, so they are lost from the model. While the effect is much smaller than in the San Joaquin scenario, the pattern seen in the two scenarios in which water flows are increased and diversions are reduced in the Sacramento River show the same response by the striped bass populations. Because the effects are subtle, more work is needed to verify the result.

To translate the above results into a summary measure, we calculated the percentage of individuals lost to the water diversion pumps. Base run estimates are 14 percent losses for 1992 and 21.5 percent losses for the 1984 run. Losses are similar to the base case for both the San Joaquin and Sacramento River scenarios in the dry water year (1992), but both scenarios reduced losses in the average water year (1984), with losses falling to 8.5 percent for the Sacramento River scenario and 11 percent for the San Joaquin River scenario. The 1992 effect is small because diversion pumping rates were very low due to the drought, but as previously mentioned, the distributional changes in 1992 caused by these two scenarios are significant because of the benefit of greater food availability in Suisun Bay. Also, our model only includes fish of less

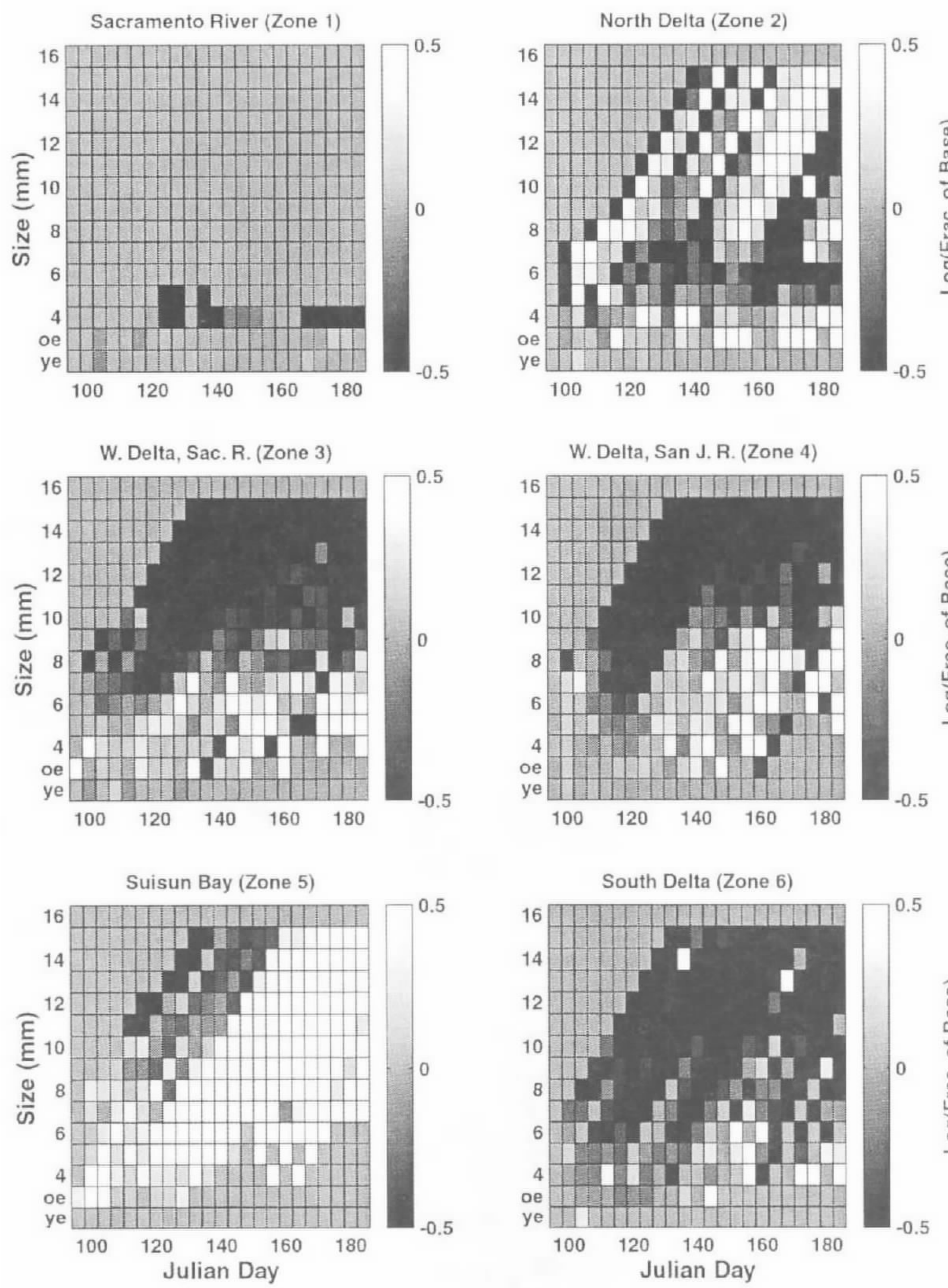

Figure 5. Fractional Change in Number of Eggs or Larvae for the 1992 CVPIA-San Joaquin River Management Scenario. (Note: The sizes of the fish are for yolk-sac and post-larvae. The OE and YE on the y-axis of each panel refer to old eggs and young eggs, respectively. The spatial zones represented by each panel are indexed to the inset map in Figure 1.

than 14.5mm, so any management benefits to larger fish are not captured in this study. In both the 1992 and 1984 water years, the IF increased losses of striped bass relative to the base case, to 25 percent in 1992, and to 27 percent in 1984. However, the increase in 1984 may not be significant.

The chinook salmon analysis focused on the IF scenario. It has been hypothesized that shifting Delta diversions from the pumping facilities in the southern Delta to a location along the Sacramento River north of the Delta near Hood would be beneficial to both water quality and ecology in the Delta. As mentioned earlier, the IF scenario generally improved the quality (i.e., reduced the salinity) of water being diverted from the Delta. However, simulation results indicate that juvenile salmon survival would be reduced due to high losses at the IF intake. Under current operating conditions in which Delta withdrawals are made at two pumping facilities in the southern Delta, juvenile salmon migrating through the Delta may become entrained in the diversion pumps. However, not all juvenile salmon migrate into the Delta. Some juvenile salmon migrate directly along the main stem of the Sacramento River into the ocean. Thus, only those juvenile salmon that migrate into the southern Delta are exposed to potential losses due to pump entrainment there. In the IF scenario, the diversion intake is located along the main stem of the Sacramento River instead of in the south Delta. Consequently, in the IF scenario, all juvenile winter-run salmon migrate downstream past the intake location and thus are exposed to potential loss at the intake. Salmon losses were assumed to be proportional to the percentage of water diverted at Hood, adjusted by a screening efficiency factor. Due to the tidal nature of the system, salmon were repeatedly exposed to potential losses at the Hood intake. Simulation results indicate that juvenile winter-run salmon mortality nearly doubled for the IF scenarios as compared to the base case. Through sensitivity analysis, the rate of salmon loss was found to depend on assumptions regarding the efficiency of the fish screen at the intake at Hood, with losses varying between 67 percent and 99 percent.

SUMMARY AND CONCLUDING COMMENTS

The fundamental objective of this analysis was to develop and use a set of interrelated simulation models to conduct a quantitative assessment of management strategies for restoring the Sacramento watershed ecosystem. Economic, hydrodynamic, water quality, and fish population models are linked to quantify impacts of proposed management alternatives. Combined outputs of these models indicate the cost to the agricultural sector of reduced water supplies, provide dynamic descriptions of physical and chemical properties of the aquatic ecosystem, and quantify impacts of these factors on selected aquatic organisms from a set of policy scenarios. This framework thus allows us to quantify the economic and environmental tradeoffs of various water management options.

We modeled two types of policy scenarios. A structural modification scenario, involving construction of a bypass canal ("Isolated Facility"), which would move the diversion point for agricultural and urban water supplies upstream of the ecologically sensitive delta (current infrastructure draws water directly from the southern Delta). This scenario changes water flows within the watershed but would not change water diversions and thus imposes no direct costs to the agricultural sector. The quality of water exported (to farms and cities) improves substantially with this scenario. Water quality also improves in portions of the central and southern Delta. Results from the fish population models are mixed. It appears as though the altered flow regime would harm both of the modeled species. Winter-run chinook salmon losses increased by 67 to 99 percent, depending on assumptions about the efficiency of fish screens at the new diversion point. The impact on striped bass was not as pronounced, but the isolated facility did increase diversion loss by 5 to 10 percent. These results likely arise from different life histories for the two species. Salmon spawning occurs in the upper reaches of the Sacramento River and all juvenile salmon migrate downstream past the new diversion point. In contrast, spawning of striped bass occurs both upstream and downstream of the new diversion point, making the population less susceptible to loss at the Isolated Facility. Moreover, this study does not include the effect of south Delta pumping on striped bass greater than 14.5mm, which may be greater than for the smaller size fish, potentially creating a benefit to the striped bass population in the system. Project construction costs are not included in this analysis but are likely to be substantial. Moreover, due to the static nature of the economic simulation models, we are not able to estimate the value of potentially increased water supply reliability, a possible benefit of the structural modification.

The second type of policy scenario considered reallocates 1.2 maf of water from farmers receiving water from the Federal Central Valley Project to fish and wildlife (reductions in agricultural water supplies are 25 percent less in a dry year). Changes in farmers' revenues associated with this policy scenario are small in aggregate percentage terms, 1 to 4 percent of base revenues, depending on the scenario. Those costs are not borne uniformly, however, and costs may be large locally, $49 million to $67 million per year for the Sacramento Valley reduction scenario or $75 million to $95 million per year in the WSJV reduction scenario. Total costs vary substantially depending on the allocation of the water diversion reductions (i.e., whether the reductions occur in the San Joaquin Valley or in the Sacramento Valley). For historical institutional reasons, the vast majority of water supply reductions to date have occurred in WSJV. These results indicate a potential to reduce total costs with a voluntary or regulatory shift of a portion of the burden to the Sacramento Valley. Striped bass populations appear to benefit from the increased flows and decreased irrigation diversions associated with these scenarios, due to reduced mortality from diversions and improved distribution within the Delta.

Importantly, reductions in irrigation diversions and accompanying increases in river flows appear to be substantially more effective in reducing fish mortality than any of the other options. However, that option is the most costly to the agricultural sector. In addition to tradeoffs between economic costs and environmental benefits, policy makers may be faced with tradeoffs among environmental indicators. Results suggest that an isolated facility could provide substantial water quality benefits in dry years. However, potential water quality benefits would have to be balanced against declines to fish species. Winter-run salmon, a species protected by the Federal Endangered Species Act, is predicted to suffer substantial declines in juvenile populations associated with the isolated facility relative to the base case. Similarly, the Isolated Facility increased diversion mortality of striped bass less than 14.5mm. However, future research is needed to clarify these results and determine whether differences are statistically significant.

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